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## A comparative study of QD and nitrogen-based 1.3 $\mu\text{m}$ VCSELs

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**Abstract.** We study two types of GaAs-based heterostructures (InAs/InGaAs quantum dots and InGaAsN quantum wells) designed for 1.3  $\mu\text{m}$  vertical-cavity surface-emitting lasers (VCSELs) and compare different device designs. A correlation between properties of the active region and parameters of the optical microcavity required for lasing was found and investigated. The comparative analysis of the vertical-cavity surface-emitting lasers with either InAs/InGaAs quantum dots or InGaAsN quantum wells active region operating in continuous wave regime at room temperature was done. Optimization of the optical microcavity provides the internal round-trip optical loss less than 0.05%.

### Introduction

Development of high-quality surface emitters for 1.3  $\mu\text{m}$  wavelength range can open way for wide use of optical fiber communications in the local area networks and potentially significantly increase the market of optoelectronic devices [1]. Have been in the last years several GaAs-based materials grown by molecular beam epitaxy (MBE) proposed as promising candidates for 1.3  $\mu\text{m}$  emitters. Among them InGaAsN quantum well (QW) and InGaAs quantum dots (QD) structures.

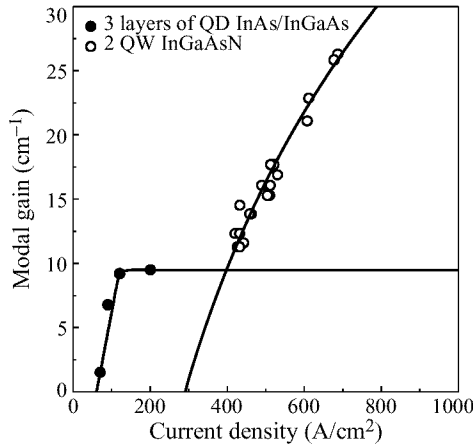
The main issues of the design of InGaAsN/GaAs VCSELs related with degradation of the optical properties at the relatively large amount of nitrogen. As a result the optical gain of 1.3  $\mu\text{m}$  emitting structures is sufficiently less than one for standard 0.98  $\mu\text{m}$  InGaAs QW structures [2]. Therefore, careful optimisation of the microcavity design and device construction is necessary for laser realization.

As for 1.3  $\mu\text{m}$  QD structures the basic problem is a relatively low optical gain of the ground-state transition [3]. Because the thickness of VCSEL microcavity is typically a few  $\lambda$ , which is much less than the usual stripe length of an edge-emitting laser, the output loss in VCSEL can significantly exceed the saturated gain of the QD active region.

In this contribution we study two types of MBE-grown GaAs-based heterostructures (InAs/InGaAs QD and InGaAsN QW) designed for 1.3  $\mu\text{m}$  VCSELs and compare different device designs.

### Devices design

Figure 1 shows optical gain curves for InGaAsN QW and InAs/InGaAs QD structures estimated from experimental results on Jth for broad-area edge-emitting lasers of various length [2,3]. InGaAsN structure demonstrates much high gain as compare to QD structure. Therefore proper design of the optical microcavity is a especially critical point for QD VCSELs. Assuming the maximum QD gain of  $12\text{ cm}^{-1}$  [3], the minimum reflectivity of DBR is estimated to be 0.9994–0.9998 depending on the internal loss. In the standard VCSEL design the main contribution fo internal loss is associated with light absorption in



**Fig. 1.** Dependence of modal optical gain on current density for laser diodes with active region based on three planes of InAs/InGaAs QDs (● ● ●) and double InGaAsN QWs (○ ○ ○).

doped distributed Bragg reflectors (DBRs). To overcome the above issues we use top and bottom AlGaO/GaAs DBRs and double current apertures in combination with intracavity contacts.

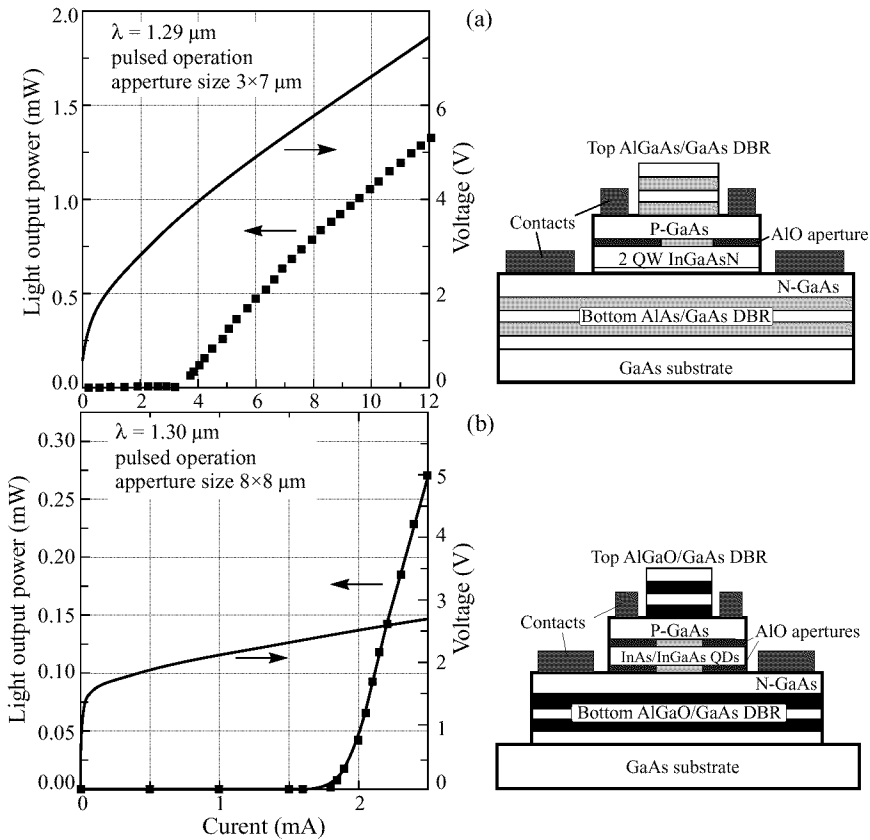
This approach provides low optical loss and suitable to realize small-size VCSELs with low threshold current as it was previously demonstrated by the first realization of QD VCSEL emitting near  $1 \mu\text{m}$  [4]. For InGaAsN VCSEL we used undoped AlGaAs/GaAs mirrors and single selectively oxidized AlGaO current aperture. Structures with AlGaO/GaAs DBRs provides relatively short effective cavity length and redistribution of the optical field intensity which leads to larger confinement factor.

## Experimental results

A schematic cross-sectional diagrams of a fabricated  $1.3 \mu\text{m}$  VCSELs are given in Fig. 2. The InGaAsN VCSEL active region contains two InGaAsN/GaAs QW separated by GaAs spacers. The QD VCSEL active region consists of three planar sheets of InAs islands formed by a 2.5 monolayer-thick InAs deposition with a 5 nm-thick  $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$  quantum well overgrowth layer and two 25 nm-thick GaAs barrier/separation layers [5]. The devices have approximately square current apertures ( $8 \times 8 \mu\text{m}$ ).

The devices were tested in pulsed and continuous wave regimes at  $25\text{--}70^\circ\text{C}$  on a temperature controlled probe station. The emission wavelength is in the  $1280\text{--}1305 \text{ nm}$  range depending on the particular position on the wafers. The room temperature pulsed light power-current (L-I) and current-voltage (I-V) characteristics of a typical InGaAsN QW and InAs-InGaAs QD VCSELs are shown in Fig. 2. The curves are for an experimental structures emitting at  $1285 \text{ nm}$  (InGaAsN QW VCSEL) and  $1300 \text{ nm}$  (QD VCSEL). The threshold currents are  $1.8 \text{ mA}$  for QD VCSEL and  $3.5 \text{ mA}$  for InGaAsN QW VCSEL. The CW output power as high as  $650 \mu\text{W}$  at drive current of  $2.8 \text{ mA}$  was observed for InAs/InGaAs QD VCSEL under continuous wave mode at  $25^\circ\text{C}$ . InGaAsN VCSEL demonstrates even higher CW output power ( $> 1 \text{ mW}$ ) and lasing up to  $65^\circ\text{C}$ .

The main difference between two fabricated devices is seems to be external quantum efficiency. In the case of QD VCSEL it is higher than  $40\%$  while for InGaAsN VCSEL less



**Fig. 2.** Schematic representation and lasing characteristics of VCSELs with active region based on double InGaAsN QWs (a) and based on three layers of InAs/InGaAs QDs (b).

than 10%. It is impossible to explain so large difference based on active material properties only. Explanation for this phenomenon may be founded from detail analysis of the structure design and device characteristics. We estimated the maximum possible values for internal optical loss for both cases and concluded that QD VCSELs demonstrates sufficiently low round trip loss ( $< 0.05\%$ ). This value is well comparable with the best results published for any type of VCSELs.

## Conclusion

Successful realization of long-wavelength InAs/InGaAs QD and InGaAsN QW VCSELs demonstrate significant potential of GaAs-based lasers for application in optical communication systems. In the case of InGaAsN VCSELs, the main attention should be paid to optimization of microcavity design. As for QD VCSELs, further work should be focused on devices with an increased number of the QD planes in the active region grown with reduced spacer thickness. This will allow us to improve the maximum QD gain that would result in long-wavelength ground-state lasing at lower Q cavities (VCSEL) with higher external differential efficiency.

### Acknowledgements

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